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(54) Title of the invention: Catadioptric Optical System

(57) Abstract

Purpose: to obtain a large numerical aperture on an image side, to secure a sufficient working distance on the image side, to reduce the size of a beam splitter, and to achieve a resolution of a quarter micron unit.

Configuration: Light from a first surface R sequentially passes through a first lens group G_1, a beam splitter BS, a concave mirror M having an enlarged magnification, the beam splitter BS, and a second lens group G_2, so as to reach a second surface W. A reduced image of the first surface R is formed on the second surface W. With this configuration, a preferable range of an imaging magnification of the concave mirror M and a preferable range of the second lens group G_2 are obtained.

What is claimed is:

Claim 1

A catadioptric optical system for forming a reduced image of a first surface on a second surface, comprising: a first lens group, a beam splitter, a concave mirror having an enlarging magnification, and a second lens group,

wherein light from the first surface sequentially passes through the first lens group and the beam splitter to be directed to the concave mirror, and the light passed through the beam splitter and reflected by the concave mirror sequentially passes through the beam splitter and the second lens group to be directed to the second surface,

wherein a rear-side principal point position of the second lens group is located on an image side with respect to a light-entering surface of the second lens group on the beam splitter side, and

wherein the catadioptric optical system satisfies the following conditions:

$-1 < 1/\beta_M < 0.5$

$0.85 < L_1 / f_2$

where β_M is an imaging magnification of the concave mirror, L_1 is a distance between the rear-side principal point position and the light-entering surface of the second lens group, and f_2 is a focal length of the second lens group.

Claim 2

The catadioptric optical system according to claim 1, wherein the catadioptric optical system satisfies the following condition:

$-1 < \beta_2 / \beta < 1$

where β is an imaging magnification of the entire catadioptric optical system, and β_2 is an imaging magnification of the second lens group.

Claim 3

The catadioptric optical system according to claim 1 or 2, wherein the beam splitter is a prism type beam splitter.

Claim 4

The catadioptric optical system according to claim 3, wherein an aperture stop is disposed in an image side including an output surface of the prism type beam splitter on the second lens group side, and wherein the catadioptric optical system satisfies the following condition:

$0.26 < D_1 / f_M < 1.00$

where D_1 is an air-converted distance between the concave mirror and the aperture stop, and f_M is a focal length of the concave mirror.

Claim 5

The catadioptric optical system according to claim 4, wherein the catadioptric optical system satisfies the following condition:

$D_2 \cdot NA/f_2 > 0.70$

where D_2 is an air-converted distance between an output surface of the beam splitter on the second lens group side and the second surface; f_2 is a focal length of the second lens group; and NA is a numerical aperture of the catadioptric optical system on the second surface side.

Claim 6

The catadioptric optical system according to claim 4 or 5, wherein the catadioptric optical system satisfies the following condition:

$(\phi_B{}^{1/2} - 4\, d_w \cdot NA) / (f_2 \cdot (NA)^2) < 4$

where ϕ_B is an area of orthogonal projection of a direction change surface of the beam splitter on the output surface on the second lens group side; d_W is a working distance of the catadioptric optical system on the second surface side; NA is a numerical aperture of the catadioptric optical system on the second surface side; and f_2 is a focal length of the second lens group.

Claim 7

The catadioptric optical system according to any one of claims 1 to 5, wherein the first lens group and the second lens group are respectively made of refractive elements including at least two different kinds of materials, and

wherein the first lens group includes a negative lens component of fluorite, and the second lens group includes a positive lens component of fluorite.

Detailed Description of the Invention

[0001]

Field of the Invention

The present invention relates to a catadioptric reduction optical system which is suitably applied to a projection optical system for reductive projection in a projection exposure apparatus used, for example, when a semiconductor device, a liquid crystal display device, or the like is manufactured by a photolithography process. In particular, it relates to a catadioptric reduction optical system having a resolution of a quarter micron unit in the ultraviolet wavelength region using a reflection system as an element thereof.

[0002]

Prior Art

In a photolithography process for manufacturing a semiconductor device or the like, there is used a projection exposure apparatus in which a pattern image of a photomask or reticle (hereinafter, collectively referred to as "reticle") is reduced to, for example, about 1/4 to 1/5 by way of a projection optical system and then the reduced pattern image is projected on a wafer (or glass plate or the like) coated with a photoresist or the like. As the integration of the semiconductor device or the like is improved, there has been a demand for a higher resolution in the projection optical system used in the projection exposure apparatus. In order to meet such a demand, there has been a demand for shortening the wavelength of illumination light and increasing the numerical aperture (N.A.) of the projection optical system.

[0003]

However, as the wavelength of the illumination light becomes shorter, a fewer kinds of glass materials can be practically used due to the light absorption. Specifically, if the wavelength of the illumination light is 300 nm or less, only synthetic quartz and fluorite can be listed as practically usable glass materials. Accordingly, if the projection optical system is formed by a refraction system alone, it becomes difficult for various aberrations such as chromatic aberration to be corrected. On the other hand, since there is no chromatic aberration in a reflection system, a technique has been proposed in which a reduction projection optical system which is provided with a so-called catadioptric optical system which combines the reflection system and the refraction system together.

[0004]

A catadioptric reduction optical system having a beam splitter which changes optical paths for performing input and output of a luminous flux with respect to a reflection system is disclosed, for example, in Japanese Unexamined Patent Publication No. H2-66510, No. H4-235516, and No. H5-72478. Here, all the concave mirrors included in the catadioptric reduction optical systems disclosed in the above-mentioned publications are convergent mirrors having a reductive magnification.

[0005]

Problem to be Solved

In the catadioptric reduction optical system in the related art as described above, since the concave mirror has the reductive magnification, the imaging magnification of a lens group which is disposed at an optical path on an image side with respect to the concave mirror is made large. Accordingly, in order to attain a larger numerical aperture in the catadioptric reduction optical system in the related art, the aperture of the beam splitter has to be enlarged approximately in proportion to the imaging magnification of the above-mentioned lens group. It results in difficulty in

manufacture as well as increase of the manufacturing cost. Also, since the concave mirror has the reductive magnification, the distance between the beam splitter and the image surface becomes short. As a result, it is difficult for the working distance on the image side to be sufficiently secured. Further, in this case, the image-forming characteristic cannot be prevented from deteriorating due to different incident angles of light beams in the luminous flux incident on a direction change surface of the beam splitter.

[0006]

Accordingly, an object of the present invention is to provide a catadioptric optical system having resolution of a quarter micron unit which can attain a large numerical aperture on the image side, can secure a sufficient working distance on the image side, and can secure the size of the beam splitter.

[0007]

Solution

In order to achieve the above-mentioned object, for example, as shown in Fig. 1, there is provided a catadioptric optical system for forming a reduced image of a first surface R on a second surface W, which includes a first lens group G_1, a beam splitter BS, a concave mirror M having an enlarging magnification, and a second lens group G_2. Further, the catadioptric optical system is configured so that light from the first surface R sequentially passes through the first lens group G_1 and the beam splitter BS to be directed to the concave mirror M; the light passed through the beam splitter BS and reflected by the concave mirror M sequentially passes through the beam splitter BS and the second lens group G_2 to be directed to the second surface W; and a rear-side principal point position of the second lens group G_2 is located on an image side with respect to a light-entering surface of the second lens group G_2 on the beam splitter BS. The catadioptric optical system satisfies the following conditions:

[0008]

$$-1 < 1/\beta_M < 0.5 \qquad (1)$$

$$0.85 < L_1 / f_2 \qquad (2)$$

Here, β_M is an imaging magnification of the concave mirror M, L_1 is a distance between the rear-side principal point position and the light-entering surface, and f_2 is a focal length of the second lens group G_2.

[0009]

Operation

In the present invention with the above described configuration, since the concave mirror M has the enlarging magnification, the second lens group G_2 can have a high positive refracting power. According to this configuration, without increasing the size of the beam splitter BS, a large numerical aperture can be obtained on the image side while securing a sufficient movable distance.

[0010]

Further, in the present invention, since an angular difference between incident angles, with respect to the direction change surface, of respective light beams in the luminous flux which passes through the beam splitter BS can be decreased, deterioration of an imaging characteristic of the beam splitter BS can be prevented. Next, conditions will be described. Condition (1) defines a preferable range of imaging magnification for the concave mirror M. Below the lower limit of this condition, it is difficult for the second lens group G_2 to have a high positive refracting power. As a result, the size of the beam splitter BS itself has to be increased in order to achieve a large numerical aperture on the image side. Under such a condition, the manufacture of the beam splitter BS becomes difficult while incurring a higher manufacturing cost. Also, under this condition, since the distance between the beam splitter BS and the image surface cannot be sufficiently secured, it becomes difficult for the optical system to secure a sufficient working distance. Further, under this condition, since the luminous flux directed toward the direction change surface of the beam splitter BS from the concave mirror M becomes a convergent luminous flux, the angular difference between the incident angles of the light beams in this luminous flux is increased, thereby deteriorating the image-forming characteristic of the optical system. Preferably, the lower limit of condition (1) is set to -0.8 and $-0.8 < 1/\beta_M$.

[0011]

Further, above the upper limit of condition (1), since the positive refracting power carried by the convex mirror M is decreased, it becomes difficult for aberrations to be corrected. Also, in order to favorably correct aberrations, it is preferable that the upper limit of condition (1) is set to 0.2 and $1/\beta_M < 0.2$. Condition (2) defines a preferable configuration of the second lens group G_2. Here, in a case where the second lens group G_2 does not satisfy condition (2), that is, below the lower limit of condition (2), the aperture of the beam splitter BS has to become large and also it becomes difficult for the working distance on the image side to be practically secured at a sufficient level. Here, it is preferable that the upper limit of condition (2) is set to 6.0 and $L_1/f_2 < 6.0$. Above this upper limit, when a larger numerical aperture is to be obtained, it becomes difficult for aberrations to be corrected and also the total length of the optical system has to become inappropriately long. The optical system under such a condition is inappropriate as a projection optical system used in a semiconductor manufacturing apparatus. Further, in the present invention, in order to obtain a larger numerical aperture and to reduce the size of the beam splitter BS, it is preferable that the lower limit of condition (2) is set to 1.35 and $1.35 < L_1/f_2$.

[0012]

Further, the beam splitter BS in the present invention is preferably a polarizing beam splitter which splits light according to a polarizing direction. In this case, a $\lambda/4$

plate is disposed in an optical path between the beam splitter BS and the concave mirror M. Also, when the imaging magnification of the entire catadioptric optical system in accordance with the present invention is β, the imaging magnification β_2 of the second lens group G_2 preferably satisfies the following condition.

[0013]

$-1 < \beta_2/\beta < 1$ (3)

Condition (3) defines a preferable range of the imaging magnification of the second lens group G_2. Below the lower limit of condition (3), the condition is unfavorable in that a large numerical aperture cannot be obtained without increasing the aperture of the beam splitter BS. Also, above the upper limit of condition (3), it is unfavorable in that the refracting power carried by the refractive optical elements (for example, the first lens group G_1 and the second lens group G_2) in the catadioptric optical system of the present invention becomes too high, namely, the effect of the reflective optical element (concave mirror M) on the catadioptric optical system becomes small, thereby making it difficult for aberrations to be corrected.

[0014]

In the present invention, the beam splitter BS is preferably a prism type beam splitter. Further, an aperture stop AS is preferably disposed on the image side including the output surface of the prism type beam splitter. Here, the aperture stop AS is preferably disposed so as to satisfy the following condition:

$0.26 < D_1/f_M < 1.00$ (4)

Here, D_1 is an air-converted distance between the concave mirror M and the aperture stop AS, and f_M is a focal length of the concave mirror M.

[0015]

Here, the air-converted distance refers to a reduced distance defined as the sum of the ratios of the respective distances of respective mediums to their refractive indexes. Assuming that the air-converted distance is d_t, the distance of the individual medium is d_i, and the refractive index of the individual medium is n_i, the air-converted distance is represented by the following expression.

[0016]

$dt = \Sigma i\ (di/ni)$

[0017]

Condition (4) defines a preferable range for the position of the aperture stop AS. Below the lower limit of this condition, the aperture stop AS is too close to the concave mirror M or the focal length of the concave mirror M is too long. In this case, it becomes difficult for the beam splitter BS to reduce its size. Also, it becomes difficult for the angular difference between the incident angles of the light beams incident on the direction change surface to be reduced. Here, below the lower limit of condition (4), even in a case where the catadioptric optical system in accordance with

the present invention satisfies the above-mentioned conditions (1) and (3), a practically sufficient working distance cannot be obtained on the image side, and it becomes difficult for the aperture stop AS to be disposed in the manufacture thereof. On the other hand, above the upper limit of conditional (4), it becomes difficult for off-axis aberrations of the luminous flux, in particular, coma aberration to be corrected.

[0018]

Further, assuming that the air-converted distance between the output surface of the beam splitter BS on the side of the second lens group G_2 and the second surface W is D_2, the focal length of the second lens group G_2 is f_2, and the numerical aperture of the catadioptric optical system on the side of the second surface W is NA, the catadioptric optical system in accordance with the present invention preferably satisfies the following condition:

$D_2 \cdot NA/f_2 > 0.70$ (5)

Condition (5) defines a preferable distance between the beam splitter and the image surface. If condition (5) is not satisfied, a space for disposing the second lens group G_2 becomes too small to secure a practically sufficient working distance on the image side. In this case, the number of the refractive optical elements constituting the second lens group G_2 is limited, thereby making it difficult for aberrations to be corrected. Also, if condition (5) is not satisfied, it becomes difficult for the second lens group G_2 to be configured so as to satisfy the above-mentioned condition (3). In order to achieve a large numerical aperture on the image side and reduce the size of the beam splitter while securing a sufficient working distance on the image side, it is preferable that the upper limit in condition (5) is set to 1.0 and $D_2 \cdot NA/f_2 < 1.0$.

[0019]

Further, the present invention is preferably configured to satisfy the following condition (6):

$(\phi_B{}^{12} - 4\, d_w \cdot NA) / (f_2 \cdot (NA)^2) < 4$ (6)

Here, ϕ_B is an area of an orthogonal projection of the direction change surface of the beam splitter BS on the output surface on the side of the second lens group G_2, d_w is a working distance of the catadioptric optical system on the side of the second surface W, NA is a numerical aperture of the catadioptric optical system on the side of the second surface W, and f_2 is a focal length of the second lens group G_2.

[0020]

Condition (6) defines a preferable range of the focal length of the second lens group G_2 with respect to the numerical aperture on the image side, the working distance on the image side, and the aperture of the beam splitter. If condition (6) is not satisfied, it becomes difficult for the optical system to be manufactured. Also, in a case where a thin film is disposed on the direction change surface of the beam splitter

BS or a $\lambda/4$ plate is provided in the beam splitter BS, the amount of wave aberration generated here becomes noticeable, thereby resulting in a remarkable image deterioration. Further, in order to facilitate the manufacture of the optical system and improve its image-forming characteristic, it is preferable that the upper limit of condition (6) is set to 3.5 and $(\phi_B{}^{1/2} - 4 d_w \cdot NA) / (f_2 \cdot (NA)^2) < 3.5$.

[0021]

Further, in the catadioptric optical system in accordance with the present invention, in order to correct chromatic aberration while obtaining a resolution of a quarter micron unit in light having a wavelength of 300 nm or less, it is preferable that the first lens group G_1 and the second lens group G_2 include the refractive elements made of at least two different kinds of materials. In this case, it is preferable that the first lens group G_1 has a negative lens component of fluorite and the second lens group has a positive lens component of fluorite.

[0022]

With this configuration, magnification chromatic aberration can be corrected by the first lens group G_1 having the negative lens component made of fluorite, while axial chromatic aberration can be corrected by the second lens group G_2 having the negative lens component made of fluorite. Also, in the present invention, since the magnification of the concave mirror M is configured so as to satisfy the above-mentioned condition (1), a sufficient space can be secured for the second lens group G_2 which is to be disposed between the beam splitter BS and the second surface W. Accordingly, as the refractive elements in the respective lens groups are configured as mentioned above, the catadioptric optical system can correct chromatic aberration while achieving a resolution of a quarter micron unit in light having a wavelength of 300 nm or less.

[0023]

In the present invention, the luminous flux between the beam splitter and the second lens group is preferably an afocal luminous flux. Further, in the present invention, a lens group for correcting aberrations may be disposed between the beam splitter BS and the concave mirror M.

[0024]

Detailed Description of Embodiments

Hereinafter, embodiments according to the present invention will be described with reference to the following drawings. Fig. 1 is an optical path diagram illustrating an optical configuration of a catadioptric optical system according to a first embodiment of the invention. In Fig. 1, an illumination optical system (not shown) illuminates a reticle R, in which a predetermined pattern has been formed, with illumination light of ArF excimer laser, for example. Light from the reticle R, after passing through a first lens group G_1, passes through a direction change surface

of a beam splitter BS, and then is reflected by a concave reflecting mirror M so as to re-enter the beam splitter BS. The light from the concave mirror M, after being reflected by the direction change surface of the beam splitter BS, passes through an aperture stop AS which is disposed at the beam splitter BS which faces an output surface, and then passes through a second lens group G_2 to reach a wafer W. On the wafer W, a reduced image of the reticle R is formed.

[0025]

In this embodiment, the beam splitter BS includes two rectangular prisms which are joined together. On the slant surface of one of the rectangular prisms, a thin film is deposited. In this embodiment, the thin film on the joint surface of the beam splitter BS functions to transmit the light from the first lens group G_1 and to reflect the light from the concave mirror M.

[0026]

Next, a lens configuration of each lens group in the first embodiment will be described with reference to Fig. 1. The first lens group G_1 includes, in the following order from an object side, a positive lens component L_{1a} having a biconvex shape of which a stronger convex surface is directed toward the beam splitter BS; a negative lens component L_{1b} having a biconcave shape; a positive lens component L_{1c} having a biconvex shape; a negative lens component L_{1d} having a meniscus shape whose convex surface is directed toward the object; a negative lens component L_{1e} having a meniscus shape whose convex surface is similarly directed toward the object; a positive lens component L_{1f} having a meniscus shape whose concave surface is directed toward the object; a negative lens component L_{1g} having a biconcave shape; and a negative lens component L_{1h} whose convex surface is directed toward the object.

[0027]

Further, the second lens group G_2 includes, in the following order from the side of the aperture stop AS, a negative lens component L_{2a} having a biconcave shape; a positive lens component L_{2b} having a biconvex shape; a negative lens component L_{2c} having a biconcave shape; a positive lens component L_{2d} having a biconvex shape; a positive lens component L_{2e} having a biconvex shape; a positive lens component L_{2f} having a biconvex shape in which a stronger convex surface is directed toward the aperture stop AS; a positive lens component L_{2g} having a biconvex shape in which a stronger convex surface is similarly directed toward the aperture stop AS; a negative lens component L_{2h} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a positive lens component L_{2i} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a negative lens component L_{2j} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a positive lens component L_{2k} having a meniscus shape whose convex surface is

directed toward the aperture stop AS; and a positive lens component L_{21} having a meniscus shape whose convex surface is similarly directed toward the aperture stop AS.

[0028]

In the following Table 1, values of items in this embodiment are listed. In this embodiment, the magnification of the whole system is 1/4 (reduction), the numerical aperture NA on the side of the wafer W is 0.6, and the working distance on the side of the wafer W is 15.0 mm. Further, as shown in Fig. 2 which is a plan view illustrating an exposure area on the wafer W in the catadioptric optical system in accordance with the present embodiment, the catadioptric optical system in the first embodiment has a slit-like exposure area of 30 mm × 6 mm in the range where the image height on the wafer W from an optical axis Ax is 15.3 mm or less. Also, the beam splitter BS in this embodiment has a rectangular parallelepiped shape of 170 mm × 170 mm × 190 mm.

[0029]

Further, in Table 1, a radius of curvature r, a surface distance d, and glass material of each surface are indicated for the individual surfaces in a sequential manner, from the first surface which corresponds to a pattern-forming surface of the reticle R as the object surface, toward the second surface which corresponds to the surface of the wafer W as the image surface. In Table 1, the sign of the radius of curvature r in each surface is set positive when the convex surface is directed toward the reticle R between the reticle R and the concave mirror M and is set positive when the convex surface is directed toward the beam splitter BS between the beam splitter BS and the wafer W. Also, the sign of the surface distance d is set negative in the optical path from the concave mirror M to the direction change surface of the beam splitter BS while it is set positive in the other optical paths. Further, as the glass materials, CaF_2 and SiO_2 represent fluorite and silica glass, respectively. Here, refractive indexes of silica glass and fluorite at the standard wavelength used (i.e., wavelength of ArF laser: $\lambda = 193.4$ nm) are as follows:

Silica glass: 1.56019

Fluorite: 1.50138

[0030]

TABLE 1 [First Embodiment]

d0 = 94.539

	r	d	Glass Material
1	-5313.040	42.330	SiO_2
2	-329.118	23.191	
3	-454.958	18.864	CaF_2
4	272.492	31.123	

5	338.834	31.042	SiO_2
6	-344.186	0.500	
7	229.022	45.000	SiO_2
8	184.586	2.298	
9	208.542	45.000	SiO_2
10	1732.582	56.174	
11	-4435.970	42.860	SiO_2
12	-244.757	0.500	
13	-288.840	45.000	CaF_2
14	233.444	5.342	
15	433.000	29.121	SiO_2
16	268.594	10.042	
17	0.000	170.000	SiO_2 Beam splitter BS
18	0.000	10.000	
19	-623.184	-10.000	Concave mirror M
20	0.000	-85.000	SiO_2
21	0.000	85.000	SiO_2 Direction change surface
22	0.000	20.000	
23	0.000	22.917	Aperture stop AS
24	-246.212	19.407	SiO_2
25	1018.290	0.657	
26	1228.970	32.523	CaF_2
27	-190.064	0.500	
28	-191.929	15.000	SiO_2
29	424.920	1.933	
30	503.632	37.933	CaF_2
31	-260.380	0.500	
32	441.375	32.753	CaF_2
33	-563.177	0.500	
34	378.243	23.321	CaF_2
35	-13558.170	0.500	
36	152.386	44.866	CaF_2
37	3098.000	0.500	
38	2231.920	15.006	SiO_2
39	296.582	0.533	
40	123.151	38.469	CaF_2
41	7856.190	0.815	
42	7240.660	15.000	SiO_2
43	74.423	7.394	

44	103.429	35.012	CaF_2
45	292.945	1.711	
46	192.719	34.643	SiO_2
47	1452.820	15.000	

The condition correspondence values of the first embodiment will be listed hereinafter.

(1) $1/\beta_M = -0.062$

(2) $L_1/f_2 = 1.842$

(3) $\beta_2/\beta = -0.10$

(4) $D_1/f_M = 0.45$

(5) $D_2 \cdot NA / f_2 = 1.37$

(6) $(\phi_B{}^{12} - 4d_W \cdot NA) / (f_2 \cdot (NA)^2) = 3.03$

Fig. 3 illustrates transverse aberrations of the first embodiment. Here, Fig. 3 (a) is a transverse aberration diagram at a 100% image height (image height at 15.3 mm); Fig. 3 (b) is a transverse aberration diagram at a 50% image height (image height at 7.65 mm); and Fig. 3 (c) is a transverse aberration diagram at a 0% image height (on the optical axis: image height of 0.0 mm). In each transverse aberration diagram, a continuous line indicates an aberration curve at the standard wavelength (λ=193.4 nm), a dotted line indicates an aberration curve at a wavelength of λ=193.5 nm, an alternate long and short dash line indicates an aberration curve at a wavelength of λ=193.45 nm, a broken line indicates an aberration curve at a wavelength of λ=193.35 nm, and an alternate long and two short dashes line indicates an aberration curve at a wavelength of λ=193.3 nm. In view of each aberration diagram shown in Fig. 3, it is understood that aberrations are favorably corrected in the catadioptric optical system in this embodiment in spite of the fact that a very large numerical aperture NA=0.6 is obtained. In particular, it is understood that chromatic aberration in the range of 193.4 nm ± 0.1 nm is corrected, thereby representing an excellent image-forming characteristic. Next, a second embodiment in accordance with the present invention will be described with reference to Fig. 4. Fig. 4 is an optical path diagram illustrating a configuration of the catadioptric optical system in the second embodiment according to the present invention.

[0031]

Since a basic configuration of the catadioptric optical system shown in Fig. 4 is substantially the same as that of the catadioptric optical system in the first embodiment shown in Fig. 1, its description is omitted and only a lens configuration of each lens group will be described. In Fig. 4, the first lens group G_1 includes, in the following order from the object side, a negative lens component L_{1a} having a meniscus shape whose convex surface is directed toward the object; a positive lens

component L_{1b} having a biconvex shape; a positive lens component L_{1c} having a biconvex shape; a negative lens component L_{1d} having a biconcave shape; a positive lens component L_{1e} having a meniscus shape whose concave surface is directed toward the object; a negative lens component L_{1f} having a biconcave shape; and a negative lens component L_{1g} having a meniscus shape whose convex surface is directed toward the object.

[0032]

Further, the second lens group G_2 includes, in the following order from the side of the aperture stop AS, a negative lens component L_{2a} having a biconcave shape; a positive lens component L_{2b} having a biconvex shape; a negative lens component L_{2c} having a biconcave shape; a positive lens component L_{2d} having a biconvex shape; a positive lens component L_{2e} similarly having a biconvex shape; a positive lens component L_{2f} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a positive lens component L_{2g} having a biconvex shape in which a stronger convex surface is directed toward the aperture stop AS; a negative lens component L_{2h} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a positive lens component L_{2i} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a negative lens component L_{2j} having a biconcave shape in which a stronger concave surface is directed toward the wafer W; a positive lens component L_{2k} having a meniscus shape whose convex surface is directed toward the aperture stop AS; and a positive lens component L_{2l} having a meniscus shape whose convex surface is similarly directed toward the aperture stop AS. In the following Table 2, values of items in this embodiment are listed. In this embodiment, as in the case of the above-mentioned first embodiment, the magnification of the whole system is 1/4 (reduction), the numerical aperture NA on the side of the wafer W is 0.6, and the working distance on the side of the wafer W is 15.0 mm. Further, as in the case of the first embodiment, the catadioptric optical system in this second embodiment has a slit-like exposure area of 30 mm × 6 mm in the range where the image height on the wafer W from the optical axis Ax is 15.3 mm or less. Also, the beam splitter BS in this embodiment has a rectangular parallelepiped shape of 170 mm × 170 mm × 190 mm.

[0033]

Further, in Table 2, a radius of curvature r, a surface distance d, and glass material of each surface are indicated for the individual surfaces in a sequential manner, from the first surface which corresponds to the pattern-forming surface of the reticle R as the object surface, toward the second surface which corresponds to the surface of the wafer W as the image surface. In Table 2, the sign of the radius of curvature r in each surface is set positive when the convex surface is directed toward the reticle R between the reticle R and the concave mirror M and is set positive when

the convex surface is directed toward the beam splitter BS between the beam splitter BS and the wafer W. Also, the sign of the surface distance d is set negative in the optical path from the concave mirror M to the direction change surface of the beam splitter BS while it is set positive in the other optical paths. Further, as the glass materials, CaF_2 and SiO_2 indicate fluorite and silica glass, respectively. Here, refractive indexes of silica glass and fluorite at the standard wavelength used (wavelength of ArF laser: λ=193.4 nm) are as follows:

Silica glass: 1.56019

Fluorite: 1.50138

[0034]

TABLE 2 [Second Embodiment]

d0 = 111.403

	r	d	Glass Material	
1	5471.605	15.000	CaF_2	
2	272.290	2.678		
3	277.567	31.750	SiO_2	
4	-278.590	0.500		
5	307.964	38.658	SiO_2	
6	-321.548	0.500		
7	-307.926	28.172	CaF_2	
8	185.540	116.871		
9	-6054.190	45.000	SiO_2	
10	-326.561	3.925		
11	-437.618	18.547	CaF_2	
12	429.454	3.774		
13	791.303	28.999	CaF_2	
14	197.545	13.348		
15	0.000	170.000	SiO_2	Beam splitter BS
16	0.000	10.000		
17	-600.094	-10.000		Concave mirror M
18	0.000	-85.000	SiO_2	
19	0.000	85.000	SiO_2	Direction change surface
20	0.000	5.000		
21	0.000	18.267		Aperture stop AS
22	-228.968	15.000	SiO_2	
23	602.629	1.000		
24	596.556	39.120	CaF_2	
25	-193.759	0.500		
26	-198.735	15.599	SiO_2	

27	414.383	1.371	
28	466.129	43.827	CaF_2
29	-250.352	0.500	
30	607.920	26.660	CaF_2
31	-570.532	0.500	
32	319.703	24.752	CaF_2
33	5248.170	0.500	
34	150.926	44.958	CaF_2
35	-11154.640	0.500	
36	6931.942	15.000	SiO_2
37	324.944	0.500	
38	123.172	38.693	CaF_2
39	27743.950	0.506	
40	-22043.850	15.000	SiO_2
41	73.840	8.552	
42	103.200	33.698	CaF_2
43	346.408	1.818	
44	217.213	33.291	SiO_2
45	1371.742	15.000	

The condition correspondence values of the second embodiment are listed hereinafter.

(1) $1/\beta_M = -0.077$

(2) $L_1/f_2 = 1.924$

(3) $\beta_2/\beta = -0.13$

(4) $D_1/f_M = 0.41$

(5) $D_2 \cdot NA/f_2 = 1.31$

(6) $(\phi_B{}^{1/2} - 4d_W \cdot NA) / (f_2 \cdot (NA)^2) = 3.09$

Fig.5 illustrates transverse aberrations of the second embodiment. Here, Fig. 5 (a) illustrates a transverse aberration diagram at a 100% image height (image height at 15.3 mm); Fig. 5 (b) illustrates a transverse aberration diagram at a 50% image height (image height at 7.65 mm); and Fig. 5 (c) illustrates a transverse aberration diagram at a 0% image height (on the optical axis: image height of 0.0 mm). In each transverse aberration diagram, a continuous line indicates an aberration curve at the standard wavelength (λ=193.4 nm), a dotted line indicates an aberration curve at a wavelength of λ=193.5 nm, an alternate long and short dash line indicates an aberration curve at a wavelength of λ=193.45 nm, the broken line indicates an aberration curve at a wavelength of λ=193.35 nm, and an alternate long and short dashes line indicates an aberration curve at a wavelength of λ=193.3 nm. In view of each aberration diagram

shown in Fig. 5, it is understood that aberrations are favorably corrected in the catadioptric optical system in this embodiment in spite of the fact that a very large numerical aperture, NA=0.6, is obtained. In particular, it is understood that chromatic aberration in the range of 193.4 nm ± 0.1 nm is corrected, thereby representing an excellent image-forming characteristic. Next, a third embodiment in accordance with the present invention will be described with reference to Fig. 6. Fig. 6 is an optical path diagram illustrating a configuration of the catadioptric optical system in the second embodiment according to the present invention.

[0035]

Since a basic configuration of the catadioptric optical system shown in Fig. 6 is substantially the same as that of the catadioptric optical system in the first embodiment shown in Fig. 1, its explanation is omitted and only the lens configuration of each lens group will be described. In Fig. 6, the first lens group G_1 includes, in the following order from the object side, a positive lens component L_{1a} having a biconvex shape in which a stronger convex surface is directed toward the beam splitter BS; a negative lens component L_{1b} having a biconcave shape; a positive lens component L_{1c} having a biconvex shape; a negative lens component L_{1d} having a meniscus shape whose concave surface is directed toward the object; a positive lens component L_{1e} having a meniscus shape whose convex surface is directed toward the object; a negative lens component L_{1f} having a meniscus shape whose concave surface is directed toward the object; a negative lens component L_{1g} having a biconcave shape; and a negative lens component L_{1h} having a meniscus shape whose convex surface is directed toward the object.

[0036]

Further, the second lens group G_2 includes, in the following order from the side of the aperture stop AS, a negative lens component L_{2a} having a biconcave shape; a positive lens component L_{2b} having a biconvex shape in which a stronger convex surface is directed toward the image; a negative lens component L_{2c} having a biconcave shape; a positive lens component L_{2d} having a biconvex shape in which a stronger convex surface is directed toward the image; a positive lens component L_{2e} having a biconvex shape in which a stronger convex surface is directed toward the aperture stop AS; a positive lens component L_{2f} having a biconvex shape in which a stronger convex surface is similarly directed toward the aperture stop AS; a positive lens component L_{2g} having a biconvex shape in which a stronger convex surface is similarly directed toward the aperture stop AS; a negative lens component L_{2h} having a biconcave shape in which a stronger concave surface is directed toward the image; a positive lens component L_{2i} having a biconvex shape in which a stronger convex surface is directed toward the aperture stop AS; a negative lens component L_{2j} having a meniscus shape whose convex surface is directed toward the aperture stop AS; a

positive lens component L_{2k} having a meniscus shape whose convex surface is directed toward the aperture stop AS; and a positive lens component L_{2l} having a meniscus shape whose convex surface is similarly directed toward the aperture stop AS.

[0037]

In the following Table 3, values of items in this embodiment are listed. In this embodiment, as in the case of the above-mentioned first embodiment, the magnification of the whole system is 1/4 (reduction), the numerical aperture NA on the side of the wafer W is 0.6, and the working distance on the side of the wafer W is 15.0 mm. As in the case of the first embodiment, the catadioptric optical system in this embodiment has a slit-like exposure area of 30 mm × 6 mm in the range where the image height on the wafer W from the optical axis Ax is 15.3 mm or less. Also, the beam splitter BS in this embodiment has a rectangular parallelepiped shape of 170 mm × 170 mm × 190 mm.

[0038]

Further, in Table 3, a radius of curvature r, a surface distance d, and glass material of each surface are indicated for the individual surfaces in a sequential manner, from the first surface which corresponds to the pattern-forming surface of the reticle R as the object surface, toward the second surface which corresponds to the wafer W surface as the image surface. In Table 3, the sign of the radius of curvature r in each surface is set positive when the convex surface is directed toward the reticle R between the reticle R and the concave mirror M and is set positive when the convex surface is directed toward the beam splitter BS between the beam splitter BS and the wafer W. Also, the sign of the surface distance d is set negative in the optical path from the concave mirror M to the direction change surface of the beam splitter BS while it is set positive in the other optical paths. Further, as the glass materials, CaF_2 and SiO_2 indicate fluorite and silica glass, respectively. Here, refractive indexes of silica glass and fluorite at the standard wavelength used (wavelength of ArF laser: λ=193.4 nm) are as follows: Silica glass: 1.56019, Fluorite: 1.50138.

[0039]

TABLE 3 [Third Embodiment]

d0 = 96.384

	r	d	Glass Material
1	1566.352	33.601	SiO_2
2	-258.445	42.686	
3	-303.358	35.000	CaF_2
4	254.513	39.688	
5	408.129	35.000	SiO_2
6	-292.562	0.500	

7	238.980	28.106	SiO_2	
8	177.718	35.520		
9	236.585	35.000	SiO_2	
10	258.786	35.249		
11	-1574.830	35.000	SiO_2	
12	-195.650	0.500		
13	-220.429	25.000	CaF_2	
14	228.713	7.071		
15	380.419	35.000	SiO_2	
16	274.848	10.847		
17	0.000	170.000	SiO_2	Beam splitter BS
18	0.000	10.000		
19	-644.053	-10.000		Concave mirror M
20	0.000	-85.000	SiO_2	
21	0.000	85.000	SiO_2	Direction change surface
22	0.000	10.000		
23	0.000	16.475		Aperture stop AS
24	-240.493	27.541	SiO_2	
25	609.289	0.500		
26	648.361	39.879	CaF_2	
27	-161.540	0.500		
28	-161.204	15.000	SiO_2	
29	432.174	2.340		
30	513.767	39.791	CaF_2	
31	-245.896	0.500		
32	397.672	35.000	CaF_2	
33	-1373.400	0.500		
34	350.822	28.205	CaF_2	
35	-1504.430	0.500		
36	152.096	44.808	CaF_2	
37	-3015.120	0.546		
38	-3831.930	15.302	SiO_2	
39	292.927	0.657		
40	122.588	34.934	CaF_2	
41	1224.997	0.539		
42	1218.161	15.188	SiO_2	
43	74.562	8.605		
44	108.074	35.000	SiO_2	
45	377.013	1.406		

46	259.877	35.000	SiO_2
47	767.722	15.000	

The condition correspondence values of the third embodiment are shown hereinafter.
(1) $1/\beta_M = -0.116$
(2) $L_1/f_2 = 2.053$
(3) $\beta_2/\beta = -0.18$
(4) $D_1/f_M = 0.40$
(5) $D_2 \cdot NA/f_2 = 1.37$
(6) $(\phi_B{}^{1/2} - 4d_W \cdot NA)/(f_2 \cdot (NA)^2) = 3.07$

Fig. 7 illustrates transverse aberrations of the third embodiment. Here, Fig. 7 (a) illustrates a transverse aberration diagram at a 100% image height (image height at 15.3 mm); Fig. 7 (b) illustrates a transverse aberration diagram at a 50% image height (image height at 7.65 mm); and Fig. 7 (c) illustrates a transverse aberration diagram at a 0% image height (on the optical axis: image height of 0.0 mm). In each transverse aberration diagram, a continuous line indicates an aberration curve at the standard wavelength (λ=193.4 nm), a dotted line indicates an aberration curve at a wavelength of λ=193.5 nm, an alternate long and short dash line indicates an aberration curve at a wavelength of λ=193.45 nm, a broken line indicates an aberration curve at a wavelength of λ=193.35 nm, and an alternate long and the two short dashes line indicates an aberration curve at a wavelength of λ=193.3 nm. In view of each aberration diagram shown in Fig. 7, it is understood that aberrations are favorably corrected in the catadioptric optical system in this embodiment in spite of the fact that a very large numerical aperture, NA=0.6, is obtained. In particular, it is understood that chromatic aberration in the range of 193.4 nm ± 0.1 nm is corrected, thereby representing an excellent image-forming characteristic.
[0040]

In the above-mentioned embodiments, the direction change surface of the beam splitter BS is preferably a polarizing splitting surface made of a dielectric multilayer film, for example. In this case, a $\lambda/4$ plate is disposed on the surface of the beam splitter BS facing the concave mirror M. Further, in a case where aberration occurs in the dielectric multilayer film, it is preferable that a thin film which eliminates the aberration occurring in the dielectric multilayer film is disposed on at least one of the surface of the beam splitter BS facing the first lens group G_1, the surface thereof facing the concave mirror M, and the surface thereof facing the second lens group G_2. Such a thin film may have a partially different thickness or refractive index, for example.
[0041]

Further, although the above-mentioned embodiments are configured such that the luminous flux which is directed from the first lens group G_1 toward the concave mirror M passes through the direction change surface of the beam splitter BS, while the luminous flux which is directed from the concave mirror M toward the second lens group G_2 is reflected by the direction change surface of the beam splitter BS, a configuration in which the luminous flux from the first lens group G_1 is reflected by the direction change surface of the beam splitter BS so as to direct to the concave mirror M, while the luminous flux from the concave mirror M passes through the direction change surface of the beam splitter BS so as to direct to the second lens group G_2 can be equivalently employed in terms of optical design.

[0042]

Effects of the Invention

As described above, according to the present invention, a large numerical aperture can be obtained on the image side, a sufficient working distance can be secured on the image side, the size of the beam splitter can be reduced, and a resolution of a quarter micron unit can be achieved.

Brief Description of the Drawings

Fig. 1

Fig. 1 is a diagram illustrating an optical path of a catadioptric optical system according to a first embodiment of the present invention.

Fig. 2

Fig. 2 is a plan view illustrating an exposure area of a catadioptric optical system according to the first embodiment.

Fig. 3

Fig. 3 illustrates transverse aberrations according to the first embodiment, in which Fig. 3 (a) represents a transverse aberration at an image height of 100%; Fig. 3 (b) represents a transverse aberration at an image height of 50%; and Fig. 3 (c) represents a transverse aberration at an image height of 0%.

Fig. 4

Fig. 4 is a diagram illustrating an optical path of a catadioptric optical system according to a second embodiment of the present invention.

Fig. 5

Fig. 5 illustrates transverse aberrations according to the second embodiment, in which Fig. 5 (a) represents a transverse aberration at an image height of 100%; Fig. 5 (b) represents a transverse aberration at an image height of 50%; and Fig. 5 (c) represents a transverse aberration at an image height of 0%.

Fig. 6

Fig. 6 is a diagram illustrating an optical path of a catadioptric optical system according to a third embodiment of the present invention.

Fig. 7

Fig. 7 illustrates transverse aberrations according to the third embodiment, in which Fig. 7 (a) represents a transverse aberration at an image height of 100%; Fig. 7 (b) represents a transverse aberration at an image height of 50%; and Fig. 7 (c) represents a transverse aberration at an image height of 0%.

Description of Symbols

G_1 first lens group

G_2 second lens group

BS beam splitter

AS aperture stop

R reticle (first surface)

W wafer (second surface)

Fig. 2

EXPOSURE AREA